PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR DILEPTON MASS RESONANCES IN $H \to 4\ell$ DECAYS USING THE CMS DETECTOR AT THE LHC

By

JAKE ROSENZWEIG

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2022

This work is dedicated to the living and loving memory of Jacob Myhre.

ACKNOWLEDGEMENTS

Without so many two- and four-legged blessings along the way, I could never have made it to this point in my academic career. Thus, I begin by giving my endless gratitude to my high energy physics mentors, Professors Andrey Korytov and Guenkah Mitselmakher, for granting me this one-of-a-kind opportunity to do real *science* at CERN.

To my wife, Suzanne Rosenzweig, for showing me that dreams *do* come true. To my mother and father, Vicki and John, who always reassured me that I could achieve anything I put my mind to. Sleep peacefully, Mom. To my siblings, Alex, Ryan, Devin, Jace, and Claudia who frequently and gently reminded me that life existed outside of grad school. To Auntie Rachel and Uncle Yuri, who just *get* me and have given to me everything I could have possible asked for. To my mentor, Sheldon Friedman, and his wife, Rita Friedman (Rosenzweig), who chose to invest in my success at a young age. I have only made it this far thanks to their undying encouragement, love, and optimism. To Sheldon's best friend, Dr. Bernard Khoury, whose reputation and has helped pave my own path. To the many moms who generously gave unconditional support during the darkest of times and unequivocal love during the brightest times: Cyndi Reilly-Rogers, Dawn Hood, Margaret Sherrill, and Silet Wiley.

To Dr. Filippo Errico for his focus, leadership, selflessness, and patience in leading the Higgs mass analysis. To Dr. Lucien Lo for showing me the simplicity and beauty of Python in his typical laid-back way and for leading the dilepton analysis. To Dr. Noah Steinberg for showing me how majestically physics can be communicated from mind to mind. To Dr. Darin Acosta, for spending many hours of physics discussion with me and the other students, who have helped us build our "CMS Office Hours" Ari Gonzalez, Cris Caballeros, Jeremiah Anglin, Sean Kent, Evan Koenig, Neha Rawal, Nik Menendez, John Rötter. To the gents who paved my way to and through the world of CMS, Brendan Regnery and Bhargav Joshi. To my mentee, Matthew Dittrich, for accepting the baton of knowledge and making everything come full circle.

To my comrades for showing me what it takes to survive the core courses, Dr. Atool Divakarla, Dr. Brien O'Brendan, Dr. Donyell Guerrero, and Dr. Vladinar Martinez. To my quondam friend, Adamya Goyal, for his gentleness, humility, patience, and tutorage. To my Polish roommates in Saint-Genis-Pouilly for showing me what home away from home feels like:

Bartoszek, Dziadziuś, Karolina, and Sandruśa. To the boys who have been there since the beginning: Jish, Willis, The Shane, Zacman, Duck, and Marcus for their clever competition and continual camaraderie which has shaped me to this day.

To Big Tree who stood as a symbol of strength, beauty, and life for centuries before us. As Irma's wild whirring winds worsened, the cacophony of ripping roots resounded throughout the western corridor. There I stood in that frozen moment—awestruck, speechless—watching her *fall* helplessly towards the physics building. What could have been a catastrophe of cataclysmic proportions was instead a gentle grazing against the north windows of NPB where, there, she was gracefully laid to rest.

Finally, to Existence, for this unpredictable, unbelievable blip of an experience called Life.

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By

Jake Rosenzweig

December 2022

Chair: Andrey Korytov
Co-Chair: Guenakh Mitselmakher
Major: Physics

The mass of the Higgs boson is measured in the $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$ ($\ell = \mathrm{e}, \mu$) decay channel and is found to be $m_{\mathrm{H}} = 125.38 \pm 0.11\,\mathrm{GeV}$; the most precise measurement of m_{H} in the world to date. The data for the measurement were produced from proton-proton (pp) collisions at the Large Hadron Collider with a center-of-mass energy of 13 TeV during Run 2 (2016–2018), corresponding to an integrated luminosity of $137.1\,\mathrm{fb}^{-1}$, and were collected by the Compact Muon Solenoid experiment. This measurement uses an improved analysis technique in which the final state muon tracks are constrained to originate from the primary pp vertex. Using data sets from the same run, a search for low-mass dilepton resonances in Higgs boson decays to the 4ℓ final state is also conducted. No significant deviation from the Standard Model prediction is observed.

CHAPTER 1
THE CMS DETECTOR

Figure 1-1. Life-size poster of the CMS detector, taken during CERN Open Days 2019 in the SX5 warehouse where parts of CMS were assembled.

Weighing in at 14 000 tonnes, standing 15 m (5 stories) tall, and reaching 29 m long, the Compact Muon Solenoid (CMS) experiment is one of the four major particle detectors at the LHC (Fig. 1-1). As shown in Fig. 1-2, CMS is situated approximately 100 m under the earth at the fifth collision point (*Point 5*) along the LHC. In 2012, both CMS and its competing experiment, A Toroidal LHC ApparatuS (ATLAS), independently discovered the Higgs boson.

Recall that the LHC (Chapter **??**) directs two proton bunches together on a collision course every 25 ns to produce thousands of new particles per pp collision. These outward-moving particles travel all sorts of directions away from the interaction point. CMS is built around the interaction point in a series of cylindrical subdetectors for nearly hermetic coverage so that most of the particles *must* travel through CMS. The detector sports a solenoid—for which CMS was named—which generates a 3.8 T uniform magnetic field that points longitudinally down the central axis of CMS. This strong magnetic field applies a Lorentz force on the outgoing charged particles, causing them to follow helical, momentum-dependent trajectories. These curved tracks separate from one another which assists in particle identification. Electrically neutral particles experience no Lorentz force and thus travel in straight lines.

The subdetectors measure the properties of the outgoing particles and carefully filter them out in a clever way (Fig. 1-3). As particles pass through the subdetectors, they interact in a variety of ways. For example, charged particles can leave "hits" in the silicon tracker system and continue through to the next radially outward subdetector, whereas hadronic matter tends to be captured by the hadronic calorimeter. Generally, hits can be reconstructed into particle tracks. From the track curvature, the charge and momentum of the particles can be deduced. Depending on *which* subdetector (or combination of subdetectors) produced signals, the type of particle can be deduced. A few example particles and their associated tracks are shown in Fig. 1-4.

Before discussing each subdetector in the following sections, it is useful to define the coordinate system used in CMS; a typical, right-handed, three-dimensional Cartesian coordinate system (x, y, z) is chosen, whose center $(0, 0, 0)$ is placed at the nominal pp collision point within CMS. The x axis points towards the center of the LHC, the y axis points vertically upward, and the z axis points westward towards the Jura mountains, tangential to the beam direction. Since CMS covers almost the entire spherical 4π steradians around the interaction point, it is convenient to use spherical coordinates (r, ϕ, θ), in which r measures the radial distance in the x-y plane, ϕ measures the azimuthal angle in the x-y plane as measured from the x axis, and θ measures the polar angle as measured from the z axis. When dealing with ultra-relativistic particles like those produced at the LHC, special-relativistic effects like length contraction must be taken into account and so the coordinate θ becomes frame-dependent. It is thus helpful to convert θ to the Lorentz-invariant quantity called pseudorapidity (η), defined as $\eta = -\ln[\tan(\theta/2)]$.

In the remainder of this chapter, the subdetectors of CMS are described in detail: the silicon tracker in Sec. **??**, followed by the electromagnetic and hadron calorimeters in Sec. **??**, then the solenoid and yoke system in Sec. **??**.

1.1 Event Selection

Amidst the chaotic particle deluge that arises from pp collisions, events are carefully selected that appear to follow the decay chain and properties of the $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$ signal. Crafting a well-designed *event selection* that identifies these signal events—while throwing away the non-signal events—is the goal. By implementing a rigorous trigger selection, vertex selection, final-state object selection, and ZZ-candidate selection, the purity of the signal process is optimized and, by extension, so is the precision on the measurement of m_{H}. The aforementioned selections are summarized in Ref. [**?**].

If an event contains more than one ZZ candidate that passes the selection criteria, then the candidate with the highest value of $\mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}}$ is selected as the overall ZZ candidate for the event.

After the full analysis selection is implemented in each of the 4ℓ final states, the expected and observed yields for the signal and background processes are given in Tables 1-1 and 1-2, which count events within the narrow signal region ($105 < m_{4\ell} < 140\,\mathrm{GeV}$) and wide signal region ($70 < m_{4\ell} < 170\,\mathrm{GeV}$), respectively.

Table 1-1. Number of expected and observed yields of signal and background processes within the narrow signal region $105 < m_{4\ell} < 140\,\mathrm{GeV}$ after the full event selection, split into the four final states.

Process	4μ	4e	$2\mathrm{e}2\mu$	$2\mu 2\mathrm{e}$	Inclusive
$\mathrm{q\bar{q}} \to \mathrm{ZZ} \to 4\ell$	88.8	38.5	63.7	41.8	232.8
$\mathrm{gg} \to \mathrm{ZZ} \to 4\ell$	9.7	4.8	4.8	3.7	23.0
RB	32.4	12.2	29.2	18.6	92.4
Sum of Background	130.9	55.5	97.7	64.1	348.2
Signal ($m_{\mathrm{H}} = 125\,\mathrm{GeV}$)	90.5	48.2	64.6	53.0	256.3
Total Expected	221.4	103.7	162.3	117.1	604.5
Total Observed	—	—	—	—	—

Table 1-2. Number of expected and observed yields of signal and background processes within the wide signal region $70 < m_{4\ell} < 170\,\mathrm{GeV}$ after the full event selection, split into the four final states.

Process	4μ	4e	$2\mathrm{e}2\mu$	$2\mu 2\mathrm{e}$	Inclusive
$\mathrm{q\bar{q}} \to \mathrm{ZZ} \to 4\ell$	486.7	192.0	246.0	170.1	1094.9
$\mathrm{gg} \to \mathrm{ZZ} \to 4\ell$	29.7	15.2	13.3	12.2	70.5
RB	70.1	30.3	61.5	42.2	204.1
Sum of Background	586.5	237.5	320.8	224.5	1369.3
Signal ($m_{\mathrm{H}} = 125\,\mathrm{GeV}$)	92.4	49.6	66.5	54.3	262.8
Total Expected	679.0	287.2	387.4	278.8	1632.3
Total Observed	—	—	—	—	—

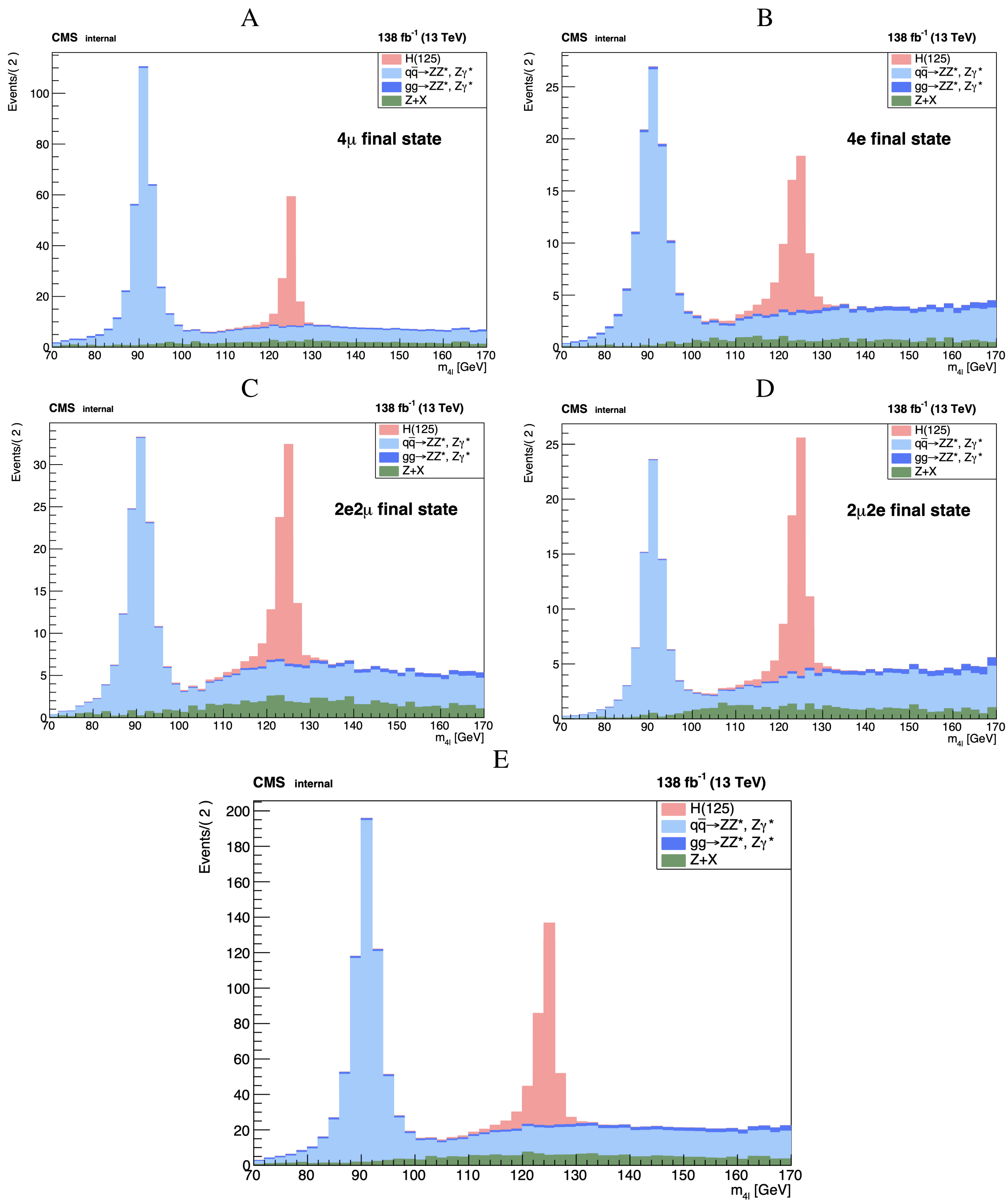

Figure 1-5. Distribution of the four-lepton invariant mass for each final state.

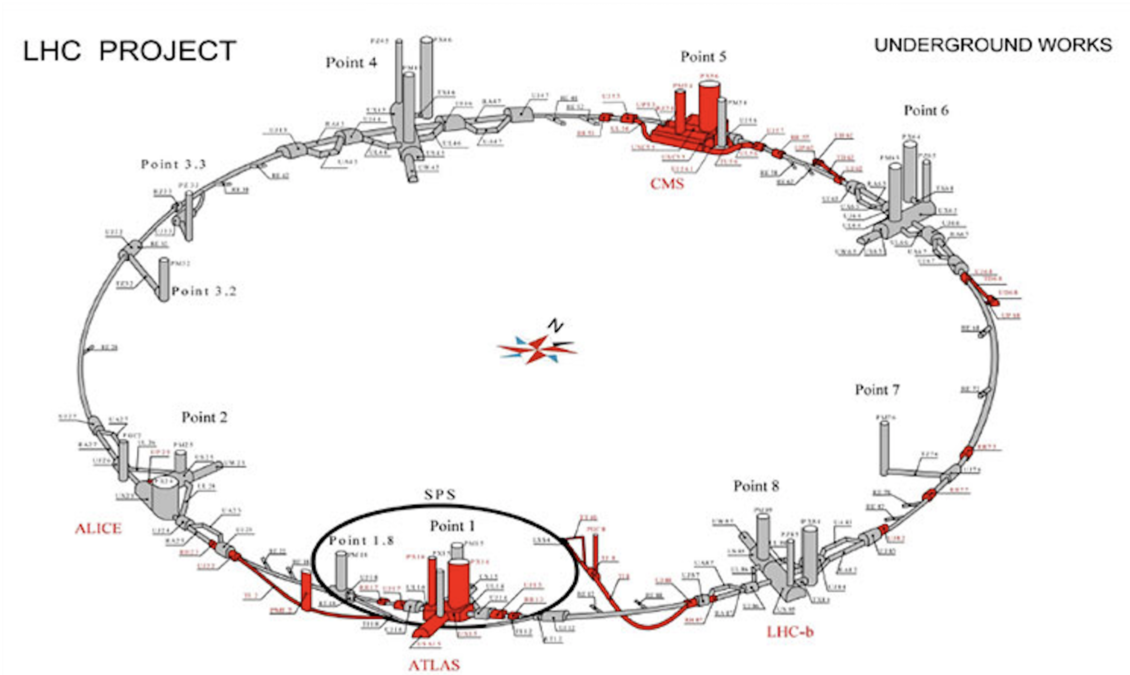

Figure 1-2. Points of interest along the LHC (Points 1–8). Collisions occur at Points 1 (ATLAS), 2 (ALICE), 5 (CMS), and 8 (LHCb), whereas the remaining points are used for LHC beam maintenance and testing.

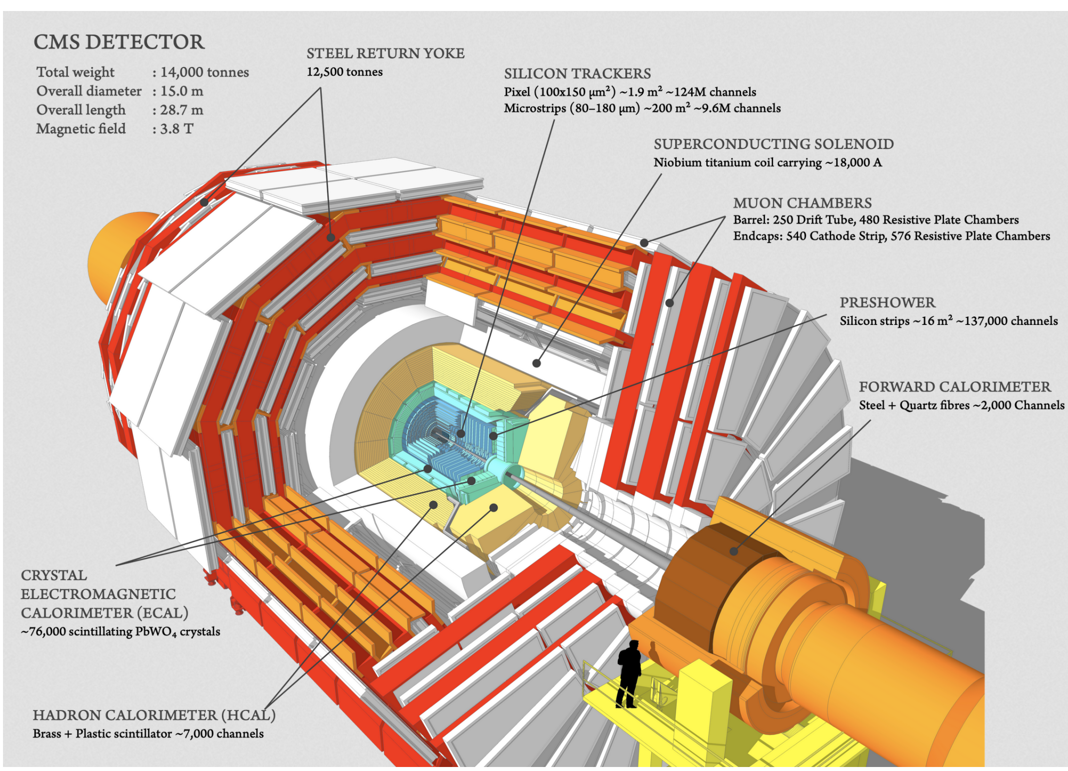

Figure 1-3. Cut out of the CMS detector showing its various subdetector components.

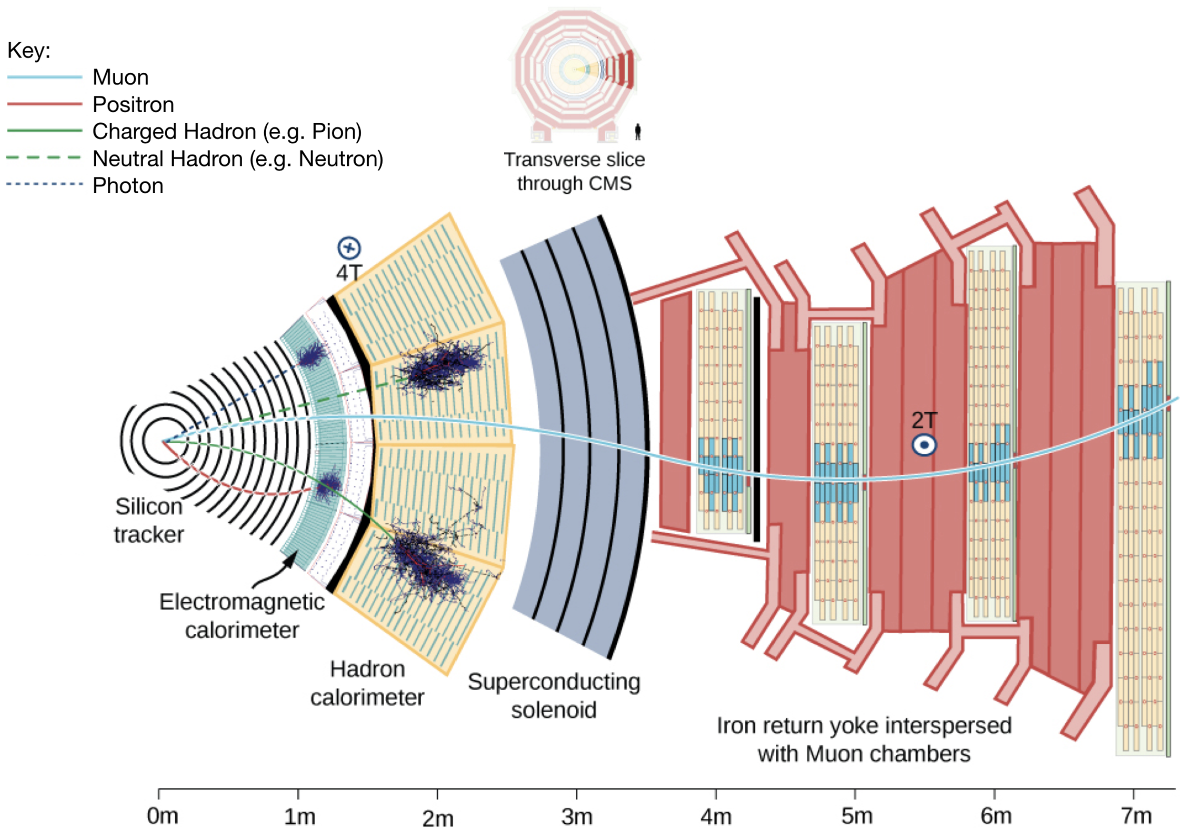

Figure 1-4. A transverse view of CMS showing the "filtration process" as different particles pass through different subdetectors. A positron (solid red line) curves due to the presence of the magnetic field and gets stopped in the ECAL, creating an EM shower. A photon (blue dashed line) does not get detected at all by the Silicon Tracker, since it has no electric charge. It continues through to the ECAL and makes a shower here, like the positron. Charged hadrons (solid green line) will show curved tracks from the Silicon Tracker, may leave some trace in the ECAL, but primarily get stopped by the HCAL creating hadronic showers. Neutral hadrons (dashed green line) do not interact with the tracker, and only undergo EM showers a little in the ECAL, but show most energy deposits in the HCAL. Muons (solid blue line) are detected by the Silicon Tracker and then mostly pass through the other subdetectors without interacting until they finally reach the Muon System. Using the Lorentz force law and knowing which direction the magnetic field is pointing, one can deduce the sign of the charge of the particle. Based on the radius of curvature from the trajectory, one can then calculate the momentum and energy of the particle.

REFERENCES

BIOGRAPHICAL SKETCH

Jake Rosenzweig had the best childhood anyone could ask for, growing up in Jacksonville, FL: enjoying video games with excellent friends, playing football on the beach, and having plenty of opportunity to make mistakes. He graduated from the University of Florida in 2011 with a B.S. in chemistry, while maintaining his sanity by getting minors in education and Latin. He enjoys building things from scrap, weightlifting, hiking in the Coloradoan mountains, gardening, silence, and—most of all—receiving the beleaguered stare from his wife after telling her a *particularly* bad dad joke.